A REVIEW OF HYPOXIA IN THE CHESAPEAKE BAY UNDER CLIMATE CHANGE

by
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Abstract

The Chesapeake Bay is the largest estuary in the United States, with high ecological and economic values. However, hypoxia occurs in the Chesapeake Bay every summer and threatens the ecosystem of the Bay. The seasonal hypoxia in the Chesapeake Bay is caused by the organic matter decompositions, intensive water stratification, and other biological and physical factors/processes. Under the stress of global climate change, Chesapeake Bay will likely experience severer hypoxia in the future. This case is because climate change affects water temperature, sea level, precipitation, river discharge, and wind strength, and consequently impacts the formation of hypoxia in the Bay. Most of the previous studies explore the effects of climate change on hypoxia in the Chesapeake Bay through qualitative discussions. Few of them quantified and predicted the impacts. This paper attempts to provide recommendations for further studies to quantify and predict the effects of climate change on hypoxia in the Bay. For further studies, it is recommended to use hydrodynamic-biogeochemical models and multimodel climate projections. More studies are needed for investigating the impacts of sea-level rise on hypoxia in the Bay and the wind changes caused by climate change. Studies could explore the effects of climate change from both hypoxic volume and hypoxic duration. Moreover, studies could take atmospheric dissolved inorganic nitrogen (DIN) and coastal DIN as variables into consideration to study the impacts of climate change. More studies are needed for understanding, quantifying, and predicting the impacts of climate change on hypoxia in the Chesapeake Bay, which will help to improve the management of Chesapeake Bay.

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1 Introduction

The Chesapeake Bay is the largest estuary in the United States (U.S.), located on the East Coast of the U.S. (Du et al., 2018). The Chesapeake Bay has high values of natural resources and economic services. It provides 3600 species of plants and animals with habitats. Moreover, it provides food, goods, beautiful scenery, and excellent properties for people (Phillips and McGee, 2016). However, hypoxia occurs in the main stem and tributaries of Chesapeake Bay every summer, threatening water quality and aquatic organisms (Phillips and McGee, 2016). Hypoxia refers to the dissolved oxygen in the aquatic environment being lower than 2 mg/L. The seasonal hypoxia in the Chesapeake Bay is the result of intensive organic carbon decomposition following spring eutrophication and isolation of bottom water caused by strong stratification in the late spring and the summer (Du et al., 2018). Previous studies showed that hypoxia negatively influenced benthic fauna, changed food web, changed nitrogen and phosphate cycling, reduced fishery catch, and increased water acidification (Du et al., 2018).

Beyond these issues, there are some stressors on the Chesapeake Bay that can be affected by climate change. Altieri and Gedan (2015) summarized that climate variables, including temperature, ocean acidification, sea-level rise, precipitation, wind, and storm patterns, would affect dead zones in estuaries and coastal seas. Irby et al. (2018) stated that climate change had net negative impacts on dissolved oxygen in coastal waters by changing temperature, sea level, and precipitation. Ross and Stock (2019) stated that climate change had the potential to affect the intensity and frequency of hypoxia in the Chesapeake Bay.

As the Chesapeake Bay is suffering the impairment from hypoxia, it is necessary to find out what hypoxia in the Bay would be like in the future under the threat of climate change. Most of the previous studies discussed the impacts of climate change on hypoxia through qualitative analysis. Few studies quantify and predict the influence of climate change on hypoxia in the Bay. *The objective of this paper is to review studies on hypoxia in the Chesapeake Bay and studies on the effects of climate change on hypoxia in the Bay to provide recommendations for further researches on quantifying and predicting the impacts of climate change on hypoxia in the Chesapeake Bay.*

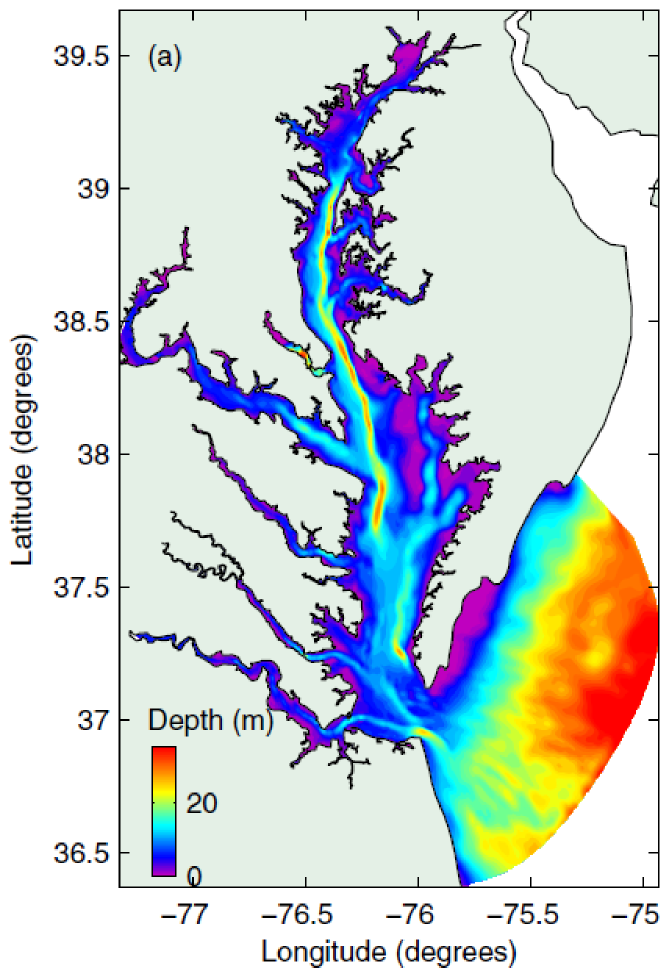

Figure 1, Bathymetry of the Chesapeake Bay, retrieved from Du and Shen (2015).

2 Method

This paper obtained information and data from scientific peer-reviewed journals and websites of governments and organizations. This paper begins with a brief introduction about hypoxia in the Chesapeake Bay in Section 3. Then, Section 4 reviews the previous studies on drivers causing hypoxia in the Chesapeake Bay. After that, Section 5 discusses the studies on how climate change influences hypoxia in the Chesapeake Bay and the studies on quantifying the impacts of climate change. Section 6 discusses the potential improvements for studying the influences of climate change on hypoxia in the Bay in the future. Finally, Section 7 gives a brief conclusion for this paper.

3 Hypoxia in the Chesapeake Bay

The Chesapeake Bay estuary is 11,000 km^2 large, and its watershed is 167,000 km^2 (Testa et al., 2017). The central channel of Chesapeake Bay is deeper than 25 m, and the length of it is more than 300 km (Bever et al., 2013; Boesch et al., 2001). Due to the weak tide mixing and deep central channel, hypoxia occurs seasonally in the main stem and tributaries of Chesapeake Bay from late spring to summer (Du et al., 2018; Phillips and McGee, 2016; Hong and Shen, 2013). Defined as when dissolved oxygen is lower than 2 mg/L, hypoxia is the result of the oxygen consumption being higher than the oxygen replenishment (Mukherjee et al., 2016).

3.1 The adverse impacts of hypoxia on the Chesapeake Bay

Hypoxia has negative influences on benthic fauna, changes food web and nitrogen and phosphate cycling, reduces fishery catch, and increases water acidification in estuarine and coastal systems (Du et al., 2018). Boesch et al. (2001) stated that hypoxia in the Chesapeake Bay adversely affected the population, diversity, and productivity of benthic animals dwelling in the deep-water region. Studivant et al. (2013) developed models demonstrating the strong positive correlation between dissolved oxygen and macrobenthic biomass in the Chesapeake Bay. The models showed hypoxia in the Bay could reduce macrobenthic production. Testa et al. (2017) stated key components of a food web could be affected by the changes in the living conditions (such as lower oxygen concentration). Consequently, the changed living conditions would alter the food web. Long et al. (2014) indicated hypoxia could reduce the population of a dominant bivalve (*Macoma balthic*) in Chesapeake by reducing egg production, which would adversely influence the ecosystem in the Chesapeake Bay in the long-term. L. Slater et al. (2020) pointed out that hypoxia in the Bay made the concentration of crustacean zooplankton (*Acartia tonsa*) and planktivorous fish (larva and juvenile *Anchoa Michilli*) become lower. Hypoxia in the Bay could cause the direct mortality of copepods. The experiments of Kraskura and Nelson (2017) showed that hypoxia negatively affected the locomotion of juvenile striped bass (*Morone saxatilis*). Hagy et al. (2004) stated hypoxia impaired the ecosystem of Chesapeake Bay.

3.2 History about hypoxia in the Chesapeake Bay

Human activities in the Chesapeake Bay watershed have grown exponentially since the early colonial period (Studivant et al., 2013). In the last century, anthropogenic activities, such as urbanization, industrial development, and fertilizer use, caused more nutrient loadings going into the Chesapeake Bay, and consequently resulted in eutrophication and hypoxia in the Bay (Boesch et al., 2001; Hagy et al., 2004; Da et al., 2018). The early observations of hypoxia in the Chesapeake Bay were at lower reaches of Potomac River in the 1910s and the main stem in the 1930s (Newcombe and Horne, 1938; Testa et al., 2017). Since 1950, the mid-summer hypoxia in the Chesapeake Bay largely and rapidly increased (Hagy et al., 2004). As the Chesapeake Bay has high ecological and economic values, governments have implemented numerous measures to reduce nutrient loadings into the Chesapeake Bay and restore the ecosystem of the Bay since the 1980s (Boesch et al., 2001). In 1983, the Chesapeake Bay Program began to conduct the restoration of the Chesapeake Bay, and state agencies and local governments signed the first *Chesapeake Bay Agreement* to control the pollution in the Chesapeake Bay (Chesapeake Bay

Program, n.d.). *The 1987 Chesapeake Bay Agreement* committed to reducing nitrogen and phosphorous loading into the Bay by 40% by 2000 (Chesapeake Bay Program, n.d.). The measures for reducing eutrophication in the Bay could restore the water quality and diminish hypoxia. However, the hypoxia volume in the Bay remained high and slightly varied since 1985 (Boesch et al., 2001). This case might indicate that the Chesapeake Bay became more vulnerable to hypoxia because of the overall degradation of the ecosystem of the Bay (Scully, 2010a). In 2010, the Environment Protection Agency started Chesapeake Bay Total Maximum Daily Load (TMDL), which limited the number of nutrients and sediment entering the Bay to improve the water quality. In 2014, TMDL was added to the goals of the *Chesapeake Bay Watershed Agreement* (Chesapeake Bay Program, n.d.)

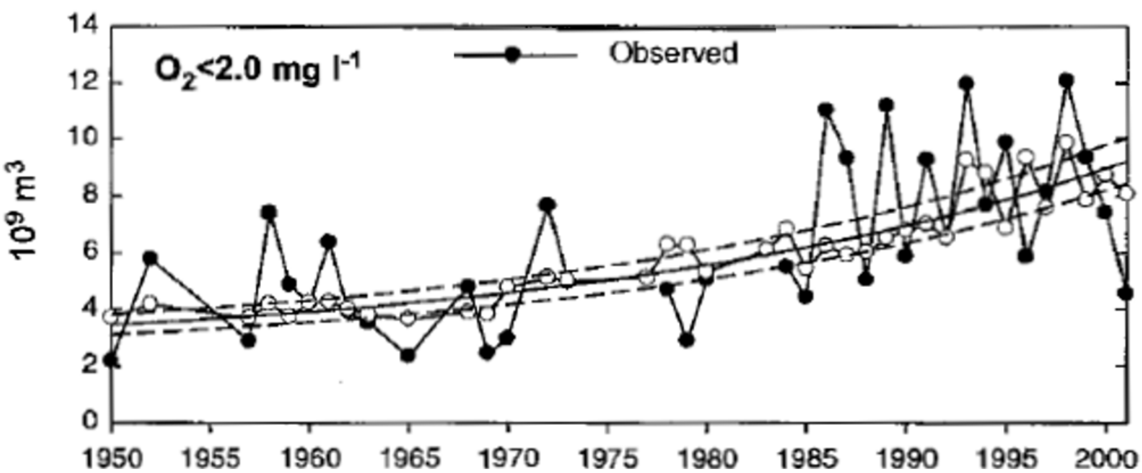

Figure 2, The historical trend of hypoxia in the Chesapeake Bay, modified from Hagy et al. (2004)

4 Drivers of hypoxia in the Chesapeake Bay

Hypoxia is the result of the collective effect of physical and biological processes exerting on the balance of oxygen consumption and oxygen replenishment (Zheng et al., 2015). Oxygen consumption includes the decomposition of organic matters and respiration of aquatic organisms, while oxygen replenishment involves atmospheric reoxygenation and photosynthesis (Cho et al., 2015). Biological processes (eutrophication and organic decompositions) and physical processes (water stratification, wind-forcing, river discharge, and temperature changing) break the balance of oxygen replenishment and consumption in the Chesapeake Bay, causing the hypoxia (Du et al., 2018). Previous studies used various methods to explore the drivers of hypoxia in the Chesapeake Bay, from observations to complex hydrodynamic-biogeochemical models.

4.1Biological factors: nutrient inputs, eutrophication, and decomposition of organic matters

Early studies believed that anthropogenic nutrient loading was one of the main drivers causing hypoxia in the Chesapeake Bay (e.g., Boesch et al., 2001). The anthropogenic nutrient loadings provide more essential elements, such as nitrogen and phosphorous, for the growth of phytoplankton. The phytoplankton generates oxygen when they grow up. However, this rapid growth of phytoplankton, known as eutrophication, as well, consumes a large amount of oxygen in water, especially in the region under the light-transmitting layer (Zheng et al., 2015). At the same time, the deaths of phytoplankton produce more organic matters into the aquatic environment (Zheng et al., 2015; Da et al., 2018). The organic matters go deep to the bottom water and decompose, leading to more oxygen consumption and hypoxia at the bottom region (Boesch et al., 2001; Zheng et al., 2015). Da et al. (2018) investigated the impacts of dissolved inorganic nitrogen (DIN) from the atmosphere, continental shelf, and rivers on the dissolved oxygen level in the Chesapeake Bay. They used the estuarine-carbon-biogeochemical model embedded in the Regional-Ocean-Modeling-System for the Chesapeake Bay (ChesROMS-ECB) to simulate hypoxia in the Bay. Atmospheric DIN exerts the adverse impacts mostly in the mesohaline region. Riverine DIN affects the largest tributaries and oligohaline Bay the most. Coastal DIN exerts influence mainly in the polyhaline area.

4.2 Physical factor: river discharge

River flow is another factor that can influence hypoxia in Chesapeake Bay. Seliger et al. (1985) found a correlation between the summertime hypoxia in the Bay and the springtime discharge from the Susquehanna River. Previous studies observed that hypoxic volume in the Chesapeake Bay during the 1950s to 1980s varied slightly when the freshwater flow was small to moderate, while largely increased when the flow was high (Boesch et al., 2001). Scully (2013) indicated that river discharge had a relationship with the interannual cycling of hypoxia in the Chesapeake Bay. Scully (2016) stated that the larger river discharge led to incremental hypoxic volume because the river discharge brought more nutrients. Besides, larger river discharge can strengthen the water stratification and reduce vertical mixing, and then cause a decline in oxygen supply to the lower water layers (Scully, 2013; Scully, 2016). However, the larger river discharge would also increase the advection of water flows, which would limit the hypoxic volume. Yet, the overall impact of larger river discharge could increase the hypoxic volume (Scully, 2013).

4.3 Other physical factors: temperature, wind force, and water stratification

Many studies suggested that nutrient inputs increase the severity of hypoxia in the coastal and estuarine systems. The hypoxic volume in the Bay remained high even though governments implemented measures to limit the nutrient loadings since the 1980s (Du and Shen, 2015). Some studies (e.g., Hagy et al., 2004) indicated that nutrient loadings poorly explained the interannual variation of hypoxia in the Chesapeake Bay. In this case, studies started to focus on the impacts of physical processes on the hypoxia in the Chesapeake Bay. Scully (2010a) used linear regressions and found a weak correlation between wind speed and hypoxia in the Bay. However, he also found a relatively stronger relationship between wind directions and the summertime hypoxic volume in the Bay. Scully (2010a) emphasized that the variation of hypoxia in the Bay could be better expressed when both nutrient loading and wind direction were considered. Scully (2013) set a three-dimensional circulation model, ChesROMS, with a constant biological oxygen utilization rate to investigate the roles of physical controls in the variation of hypoxia in the Chesapeake Bay. The physical controls were river discharge, water temperature, wind speed, and wind direction. The model showed it was the seasonal change of temperature that affected the seasonal cycle of hypoxia in the Chesapeake Bay (Scully, 2013). Since higher temperature can lower the solubility of oxygen in water, the hypoxic volume would be easily affected by temperature (Sully, 2013). The model also showed that wind forcing impacted the hypoxia variability in the Bay the most. Higher wind speed in winter increased both turbulent mixing movement and the advective movement of water parcels, hindering the formation of hypoxia (Scully, 2013). Whereas, weaker wind speed in summer led to lower turbulent mixing and advective movements of water parcels, contributing to the formation of hypoxia in the Chesapeake Bay. At the same time, the mean wind direction from east or west in summer increased anoxic volume (Scully, 2013). Du and Shen (2015) used the conceptual bottom dissolved oxygen budget model, and they found the variations of physical conditions in the Chesapeake Bay accounted for 88.8% of the interannual variations of hypoxia in the Bay. Scully (2016) used the same method with that in Scully (2013) to simulate hypoxia in the Chesapeake Bay during 1984-2013 and approved that physical controls strongly impacted the summertime hypoxic volume in the Chesapeake Bay. The model showed wind speed is the physical variable that drove the variations of hypoxic volume the most. Jiang and Xia (2018) stated that the spring algal biomass was higher on western flank than on the eastern flank of the Chesapeake Bay because of the riverine input, and the up-estuary (southerly) winds. The southerly winds enhanced the growth of spring algal biomass on the western flank of the Bay. Thus, the winds could impact hypoxia in the Bay by exerting an effect on the spring algal biomass as well. As for water stratification, it can hinder the oxygen transport from upper water layers to lower water layers, causing the low oxygen concentration level in bottom water (Hong and Shen, 2013).

Zheng et al. (2015) stated that temperature, water stratification, phytoplankton biomass, and the number of organic matters could have influences on the hypoxic volume in the coastal and marine systems. Based on the previous studies above, decomposition of organic matters, nutrient loadings, and phytoplankton biomass/eutrophication are the main biological factors affecting hypoxic volume in the Chesapeake Bay. Water temperature, water stratification, wind forcing, and river discharge are the primary physical controls exerting effects on the hypoxic volume in the Bay. Biological and physical factors have collectively effect on balance between oxygen replenishment and oxygen consumption, driving the hypoxia in the Chesapeake Bay.

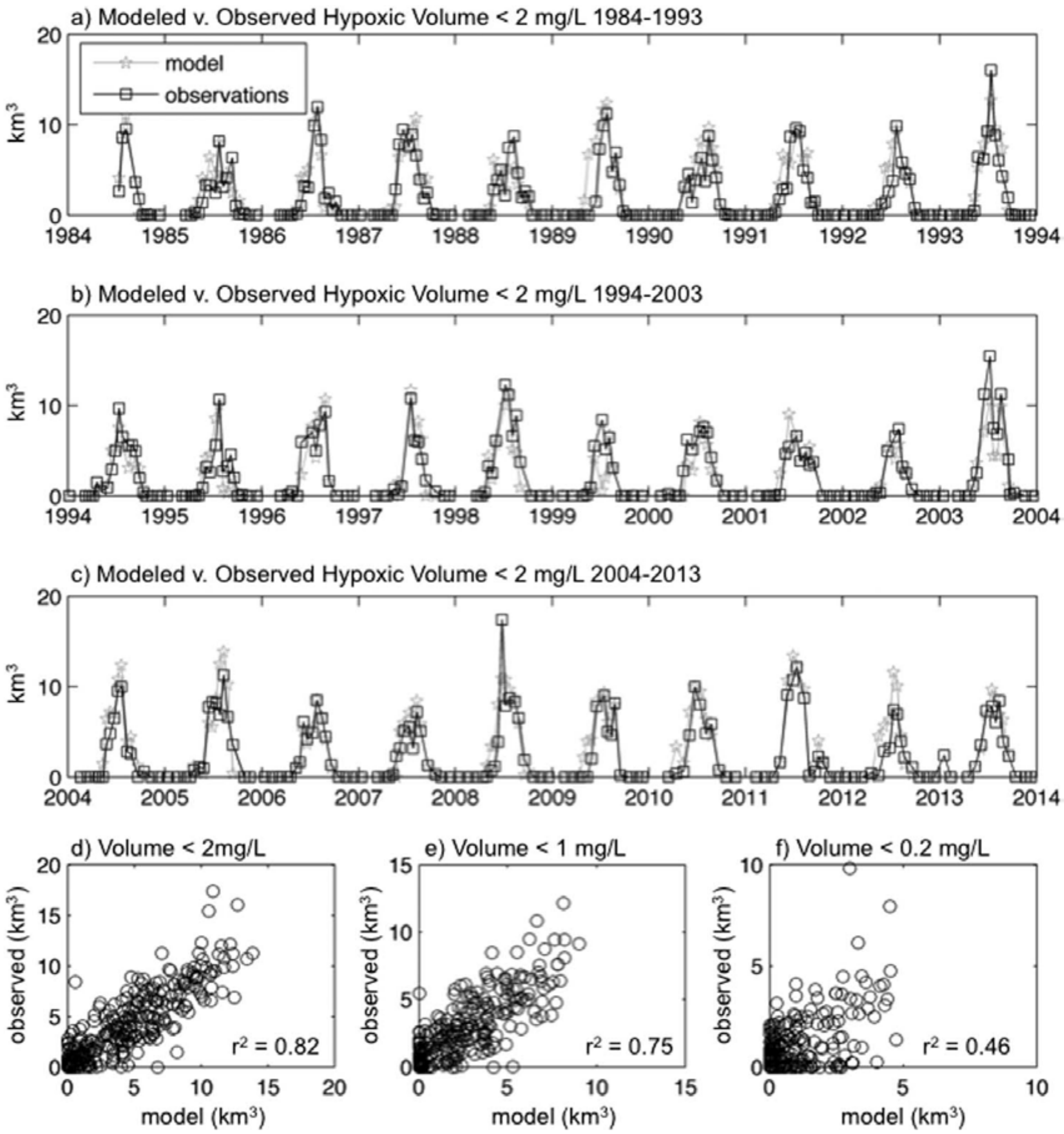

Figure 3, Comparison of the predicted hypoxic volume<2 mg/L (gray stars) to the observed (black squares) volume based on individual CBP cruises for (a) 1984–1993, (b) 1994–2003, and (c) 2004–2013. Scatter plots comparing the model prediction and observed hypoxic volumes for (d)<2 mg/L threshold, (e)<1 mg/L threshold, and (f)<0.2 mg/L threshold. Reported correlations are all significant at $p<0.05$. This entire figure is retrieved from Scully (2016), showing that the model in Scully (2016) well expressed the interannual variation of hypoxia in the Chesapeake Bay.

5 Impacts of the climate change on the hypoxia in the Chesapeake Bay

As the anthropogenic activities have grown rapidly and largely since the industrial revolution, climate change resulting from the massive emissions of greenhouse gases rises global temperature and sea level. This global change is also changing the local environment of estuarine and coastal systems (Irby et al., 2018). As an important index of water quality, dissolved oxygen in the estuarine and coastal systems is under the threat of climate change (e.g., Altieri and Gedan, 2015; Testa et al., 2017). Since the climate change can affect the level of oxygen concentration in the aquatic environment by increasing temperature, rising sea level, and altering precipitation, hypoxia in the estuarine and coastal systems has the potential to become severer (e.g., Pyke et al., 2008; Najjar et al., 2010). Hence, the seasonal and severe hypoxia in the Chesapeake Bay attracted research concerns to explore the impacts of climate change on the hypoxic volume in the Chesapeake Bay in the future. The National Centers for Coastal Ocean Science started the project, *Predicting Impacts of Climate Change on Success of Hypoxia Management Actions in Chesapeake Bay*, in September 2016. This project is for understanding how temperature and precipitation affect hypoxia in the Chesapeake Bay and helping to develop management to sustain the ecosystem of Chesapeake Bay under the changing climate (NCCOS, n.d.).

5.1 Predictions of climate change in the Chesapeake Bay

Intergovernmental Panel on Climate Change (IPCC) has published five assessment reports reviewing the latest climate science. IPCC used Special Report on Emission Scenarios (SRESs) in the Third and Fourth Assessment Reports to project future changes in climate. SRESs contain four scenario families, and they are A1 (rapid and global economic growth), A2 (regionally oriented economic growth), B1 (global environmental sustainability), and B2 (local environmental sustainability) (IPCC, 2007). IPCC's Fifth Assessment Report used the

Representative Concentration Pathway (RCP) scenarios for climate modeling. The RCPs were established based on the volume of greenhouse gases emission in the coming years. They are RCP2.6, RCP4.5, RCP6, and RCP8.5 labelled after a possible range of radiative forcing values in 2100 (IPCC, 2014). RCP 2.6 represents the scenario that the emission of greenhouse gases is strictly limited in the future. While RCP8.5 refers to the scenario that the emission of greenhouse gases is excessive in the future. According to the IPCC's projections in those scenarios, the global temperature and global sea level will increase in the future. For the Chesapeake Bay, Najjar et al. (2010) reviewed previous studies on the impact of climate change on the Chesapeake Bay. They summarized that the CO_2 concentrations would increase 50-160%, sea level would rise 0.7-1.6 m, and water temperature would increase 2-6℃ by the end of the 21st century. Hawkins (2015) used data from Coupled Model Intercomparison Project (CMIP3) and CMIP5 projections to drive a gridded hydrologic model, simulated streamflow and other hydrologic parameters of the Chesapeake Bay Watershed and made predictions about the hydrology of the Chesapeake Bay watershed under IPCC's scenarios (SRESs and RCPs). Hawkins (2015) predicted that annual average temperature would increase 1.9℃ to 5.4℃ by 2088 to 2099, and yearly total precipitation would increase between 5.2% and 15.2% by 2088 to 2099. Wagena et al. (2018) qualified the impacts of climate change and climate anomalies on hydrology, nutrient cycling, and greenhouse gas emissions in an agricultural catchment of the Chesapeake Bay watershed. They found that climate change will largely increase winter/spring flow by increasing the precipitation and temperature. However, the summer flow will decrease due to the increase of evapotranspiration in summer.

5.2 The impacts of climate change on hypoxia in the Chesapeake Bay

Hypoxia in the Chesapeake Bay is under the influence of both biological and physical processes. Climate change could exert impacts on the hypoxic volume by affecting these processes. Directly, the higher temperature, caused by climate change, will reduce the solubility of oxygen in the water and increase the water stratification by altering the density of surface water (Pyke et al., 2008; Najjar et al., 2010; Altieri and Gedan, 2015). Consequently, the increased temperature will contribute to exacerbating the hypoxia in the Chesapeake Bay, especially in summertime (Pyke et al., 2008; Najjar et al., 2010). The heavier precipitation due to climate change could expand hypoxia by strengthening stratification and nutrient loading (Altieri and Gedan, 2015). Meanwhile, sea-level rise will increase the channel depth of the Bay, increasing water stratification (Testa et al., 2017). However, sea-level rise can also increase tidal mixing to increase oxygen concentration (Testa et al., 2017). Christensen et al. (2007) stated that climate change would increase the peak wind intensities in the Chesapeake Bay. The changes in wind direction and wind speed would either increase or diminish the hypoxia in aquatic systems, which depends on the degree of the impact of wind forcing on the nutrient inputs and water stratification (Altieri and Gedan, 2015). Indirectly, a higher temperature will accelerate the rate of nutrient cycling. As a result, the growth of phytoplankton and decomposition of the dead phytoplankton will speed up and increase (Pyke et al., 2008; Najjar et al., 2010). The metabolism of aquatic organisms will increase because of the higher water temperature, which leads to higher demands for dissolved oxygen and higher hypoxic volume (Altieri and Gedan, 2015). The river discharge to the Chesapeake Bay, which is controlled by precipitation, will increase during winter and spring under the climate change (Pyke et al., 2008; Altieri and Gedan, 2015). Many studies stated that the spring river discharge was a predictor of the summertime hypoxia in the Bay because large river discharge would increase water column stratification in summer in the

Bay and result in promoting the hypoxia (Hong and Shen, 2015). Thus, river discharge also has the potential to lower the oxygen concentration in the Bay under the threat of climate change in the future. Overall, climate change would increase the severity of hypoxia in the Chesapeake Bay in the future, mainly through changing water temperature, precipitation, sea level, wind strength, and river discharge.

According to the prediction of climate change in the Chesapeake Bay made by Hawkins (2015) and Najjar et al. (2010), and the ways that climate change aggravates the hypoxia, people have reasons to pay more attention to explore, quantify and predict the impacts of climate change on hypoxia in the Chesapeake Bay in the future. Du et al. (2018) used Empirical Orthogonal Functions (EOF) analysis, a long-term numerical vertical exchange time scale (VET) simulation, and statistical analysis to investigate how the worsening physical conditions of the Chesapeake Bay caused by climate change affect the hypoxic volume in the Bay. The time series of the study spanned from 1985 to 2012. They used EOF analysis to investigate the correlations between hypoxic volume and biological and physical processes (temperature, wind, river discharge, vertical exchange time, nutrient loading, and chlorophyll-a). According to the analysis, the temperature had a strong relationship with the variations of hypoxia in the Chesapeake Bay. Still, it cannot explain the significant change of dissolved oxygen in summer. The analysis showed that the variation of hypoxia in the Bay could be expressed well only when both biological and physical processes are considered. The VET simulation in the study well explained the seasonal cycling of hypoxia in the Chesapeake Bay. According to VET simulation and statistical analysis, the upper Bay near 39N had the most server hypoxia in summer, with the longest vertical exchange time. Du et al. (2018) claimed that the warmer water temperature and more stratified water column caused by climate change would worsen the hypoxia in the Chesapeake Bay in the future. Irby et al. (2018) used the ChesROMS-ECB model and projections of climate change by mid-21st-century to study the negative impacts of climate change on hypoxia in the Chesapeake Bay and the potential success of TMDL in reducing nutrient loadings and decreasing hypoxia in the Chesapeake Bay. ChesROMS-ECB is a three-dimensional hydrodynamic-biogeochemical model used for simulating hypoxia in the Chesapeake Bay. For climatic variables, Irby et al. (2018) set sensitivity experiments to examine the individual and combined impacts of temperature change, sea-level rise, and precipitation/river discharge change on hypoxia in the Bay. They divided the Chesapeake Bay into four study regions based on the salinity difference. They used water quality data of the Bay from 1993 to 1995 because the establishment of TMDL took the water quality data from 1993 to 1995 as the reference. The results showed that warming water would decrease dissolved oxygen in the Chesapeake Bay by reducing oxygen solubility, increasing respiration of organisms, and remineralization processes. Sea-level rise would increase oxygen concentration in bottom water but decrease oxygen concentration at mid-depths because it would reduce the residence time in bottom regions but increase water stratification. The potential impacts of climate change on hypoxia in the Chesapeake Bay would be much small. Moreover, the reduction of nutrient loadings to the Bay, required by TMDL, would successfully improve the oxygen concentration in the Chesapeake Bay in the future. Ni et al. (2019) conducted downscaling climate projections and the Row-Column Aesop model embedded in the Regional-Ocean-Modeling-System model (ROMS-RCA) to predict and qualify the impacts of climate change (in A2 greenhouse gases emissions scenario) on hypoxic volume in the Chesapeake Bay. ROMS-RCA is a three-dimensional hydrodynamic-biogeochemical model for simulating hypoxia in the Chesapeake Bay. Global climate model (GCM) and regional climate models (RCMs) were used to make projections of climate in 1971-2000 (late 20th century) and 2041-2070 (mid-21st century) for driving ROMS-RCA. They focused on the impacts of sea-level rise and higher temperature caused by climate change and found that hypoxic and anoxic volumes would increase by 10-30% between the late 20th and mid-21st century. They indicated that oxygen concentration in bottom water would decrease because the sea-level rise and increased winter-spring runoff lead to stronger stratification and hinder the oxygen supply. Higher temperature accounts for 50% of the reduction of oxygen in bottom water.

Table 1, Summary of Studies: Du et al. (2018), Irby et al. (2018) And Ni et al. (2019)

Study	Du et al. (2018)	Irby et al. (2018)	Ni et al. (2019)
Study Area	the main stem of Chesapeake Bay	the main stem of Chesapeake Bay	the main stem of Chesapeake Bay
Time Series of Data	1985-2012	1993-1995	1989-1998 (reference), 2049-2058
Methods	EOF analysis, VET simulation, statistical analysis	ChesROMS-ECB, sensitivity experiments	ROMS-RCA, multimodel climate projections (RCM-GCM)
Climate Projections	--	sensitivity experiments	multimodel climate projections (RCM-GCM)

6 Discussions

Hypoxia in the Chesapeake Bay, as a harmful phenomenon towards estuarine ecosystems, attracts research concerns in the past decades. The decomposition of organic matters after the spring eutrophication and the strong stratification in the late spring and summer are the two main drivers causing hypoxia in the Chesapeake Bay (Du et al., 2018). Other factors/processes, such as nutrient inputs, water temperature, wind force, and river discharge, are also affecting the formation of hypoxia in the Chesapeake Bay. The seasonal hypoxia in the Chesapeake Bay could be severer in the future because climate change is altering water temperature, precipitation, river discharge, the sea level of the Bay, and wind strength. Consequently, climate change would affect those biological and physical factors/processes.

(1) On account of climate change in the future, higher water temperature in the Chesapeake Bay will increase hypoxia by decreasing the solubility of oxygen and increasing the demand for oxygen due to the accelerated biological activities and the decomposition of organic matters.

(2) Precipitation in the Chesapeake Bay watershed will increase in winter and spring due to climate change (Hawkins, 2015). The heavier and intensified precipitation will strengthen water stratification and increase nutrient loadings, and consequently will increase the severity of hypoxia in the Bay. Besides, precipitation will increase river discharge in winter and spring (Irby et al., 2018). The overall impacts of larger river discharge will increase the severity of hypoxia. However, high evapotranspiration in summer and the

strict implementation of TMDL will mitigate the adverse effects of heavier precipitation and larger river discharge on hypoxia in the Bay (Irby et al., 2018).

(3) Sea-level rise caused by climate change could bring more oxygen into the Bay by tidal mixing reduce oxygen concentration by increasing water stratification (Testa et al., 2017; Wang et al., 2017). Irby et al. (2018) predicted that sea-level rise would increase oxygen concentration in bottom water but decrease oxygen concentration at mid-depths in the future. However, Ni et al. (2019) stated that sea-level rise would hinder oxygen supply to the bottom water by increasing the water stratification. Further studies could investigate more on the effects of sea-level rise on hypoxia in the Chesapeake Bay.

(4) In the Chesapeake Bay, winds are strong in winter but weak in summer (Scully, 2013). Christensen et al. (2007) pointed out that the frequency of tropical cyclones in winter will decrease, but the intensities of it will increase due to climate change. Consequently, the powers of peak wind will increase in the Chesapeake Bay. Stronger winds increase oxygen concentration by increasing turbulent mixing and advective movement. However, this stronger winds in the Chesapeake Bay will appear in winter. The changes in summertime wind strength caused by climate change are uncertain. Moreover, the changes in mean wind direction caused by climate change are unknown (e.g., Pyke et al., 2008; Najjar et al., 2010). Therefore, more studies are needed to explore the changes in wind speed and wind direction caused by climate change in the future. These studies will help further studies on qualifying and predicting the impacts of climate change on hypoxia in the Chesapeake Bay.

The formation of hypoxia is the result of the imbalance between oxygen replenishment and oxygen consumption. This balance is dynamic and easily affected by biological and physical factors/processes. Therefore, hypoxia in the Bay experiences seasonal and interannual variations due to the variations and changes of those factors/processes. Meanwhile, the climate is dynamic and uncertain and affects those biological and physical factors/processes. Therefore, studies are supposed to consider various variables, and the uncertainties and variations of those variables, to investigate the influence of climate change on hypoxia in the Bay. Previous studies showed that complex dynamic models with various variables are essential for related studies. Irby et al. (2018) utilized 3D hydrodynamic-biogeochemical model, ChesROMS-ECB, to simulate hypoxia in the Chesapeake Bay. ChesROMS, a three-dimensional hydrodynamic model developed from ROMS, is the physical part of the hybrid model and commonly used to simulate the water characteristics and currents in the Chesapeake Bay (e.g., Bever et al., 2013; Scully, 2013; Scully, 2016; Da et al., 2018; Irby et al., 2018). This 3D hydrodynamic model has a 150 by 100 curvilinear grid with 20 vertical sigma levels (Scully, 2013; Scully 2016). ECB is the biogeochemical part of the whole model, containing a simplified nitrogen cycle with eleven state variables: nitrate, ammonium, phytoplankton, zooplankton, small and large detritus, semi-labile and refractory dissolved organic nitrogen, inorganic suspended solids, chlorophyll, and oxygen (Feng et al., 2015). Ni et al. (2019) used another three-dimensional hydrodynamic-biogeochemical model, ROMS-RCA, to simulate hypoxia in the Bay. ROMS is the physical component of ROMS-RCA and is also a three-dimensional hydrodynamic model for simulating physical conditions in the Chesapeake Bay. It has 82 times 122 grids in the horizontal direction and 20 vertical layers. RCA is the biogeochemical part of the model and contains water column and sediment diagenesis components. The variables of RCA include two phytoplankton groups, dissolved organic carbon, nutrients (nitrogen, phosphorous, and silicon), and oxygen. Both ChesROMS-ECB and ROMS-RCA various and essential variables that affect hypoxia in the aquatic environment. Meanwhile, both have been approved by previous studies that they are suitable for simulating oxygen concentration in the Chesapeake Bay (e.g., Da et al., 2018; Shen et al., 2018). Different from Irby et al. (2018) and Ni et al. (2019), Du et al. (2018) used VET simulation to investigate oxygen concentration in the Chesapeake Bay. The VET simulation well expressed the variation of hypoxia in the Bay and was highly sensitive to wind force. Du and Shen (2015) also showed that VET simulation is sensitive to wind force. This high sensitivity is because winds could affect turbulent mixing and advective movements of water, and then affect the vertical exchange time of water parcel. However, VET simulation was not sensitive to river discharge based on the sensitivity test (Du et al., 2018). Hence, hydrodynamic-biogeochemical models are likely more suitable for further studies to simulate oxygen concentration in the Bay and investigate the impacts of climate change on hypoxia in the Bay in the future.

As for climate projections, Ni et al. (2019) used GCM and RCMs to generate downscaled climate projections. There were three main scenarios for projections: WRFG_cgm3 (large increase in temperature and moderate streamflow), RCM_gfdl (low-temperature changes, and low streamflow), HRM3_hadcm3 (moderate temperature changes and large streamflow). These multimodel projections were useful to generate probabilistic and practical impact assessment (Ni et al., 2019). While Du et al. (2018) used EOF analysis and data from 1985 to 2012 to analyze the relationship between the oxygen concentration in the Bay and biological and physical processes; Irby et al. (2018) utilized sensitivity experiments to examine the individual and combined impacts of climate change factors. It is evident that the method of Ni et al. (2019) produced better climate change projections and is suitable for simulating hypoxia in the future. However, it would be better if climate change scenarios consider more variables. Moreover, the climate projections of Ni et al. (2019) were based on the medium-high A2 greenhouse gas emissions scenario. IPCC will release the sixth Assessment Report in 2022 (IPCC, n.d.). For more accurate climate projections, further studies are supposed to follow the latest Assessment Report or use the latest available climate data.

Besides, further studies could explore and discuss the impacts of climate change on both the duration and volume of hypoxia in the Chesapeake Bay. Irby et al. (2018) found that climate change might increase both the duration and volume of hypoxia in the Bay. Lake and Brush (2015) indicated that the duration of hypoxia in the tributary of the Chesapeake Bay would increase under the influence of climate change. Moreover, atmospheric and coastal DIN in nitrogen cycling would also affect hypoxia in the Bay. Previous studies stated that climate change would change nutrient cycling (such as nitrogen cycling) by changing temperature, precipitation, biological activities in the aquatic environment, and territorial vegetations (e.g., Pyke et al., 2008; Najjar et al., 2010; Altieri and Gedan, 2015). Da et al. (2018) indicated that atmospheric DIN had a similar impact on hypoxia as the same gram-for-gram change in riverine DIN loading. The overall effect of coastal DIN on hypoxia in the Bay was similar to that of atmospheric DIN. Atmospheric and coastal DIN exerted the largest impact on hypoxia in summer and appeared at the southern mesohaline of the Bay in wet years. Therefore, further studies could also consider atmospheric DIN and coastal DIN as variables affecting hypoxia in the Bay under climate change.

More studies are needed for quantifying and predicting the impacts of climate change on hypoxia in the Chesapeake Bay. Irby et al. (2018) stated that the effects of climate change on hypoxia in the Chesapeake Bay would be small in the future, and TMDL will successfully decrease hypoxia in the Bay. Ni et al. (2019) showed that climate change would cause a 10-30% increase in hypoxic and anoxic volume from the late 20th century to the mid-21st century.

Compare the results of Irby et al. (2018) and Ni et al. (2019), Ni et al. (2018) showed more significant impacts of climate change on hypoxia. Keeling et al. (2010) summarized many modeling studies on the oceanic dead zone. They stated that the different results of those studies were likely the result of their differences in models, assumptions, climate projections, and climate sensitivity. Similarly, Irby et al. (2018) and Ni et al. (2019) have different results, which might be the result of their differences in hydrodynamic-biogeochemical models, assumptions, and climate projections. Thus, it is hard to determine which study had correct results. Besides, Ni et al. (2019) only focused on two changes (sea-level rise and higher temperature). Therefore, more studies on quantifying and predicting the impacts of climate change on hypoxia in the Chesapeake Bay are needed. Those further studies will help the development of management for the Chesapeake Bay.

7 Conclusions

In the future, climate change will increase the severity of hypoxia in the Chesapeake Bay by affecting water temperature, sea level, precipitation, river discharge, and wind strength. To better understand, quantify, and predict the impacts of climate change on hypoxia in the Chesapeake Bay, more studies are needed. For further studies, 3D hydrodynamic-biogeochemical models and multimodel projections for climate change are suitable choices. Investigating the impacts of sea-level rise on hypoxia in the Bay and the changes in wind strength and wind direction caused by climate change needs more studies. Studies can take variables like atmospheric DIN and coastal DIN into consideration. Moreover, studies can explore the impact of climate change on hypoxia from both hypoxic volume and hypoxic duration. Further studies will improve the management of Chesapeake Bay.

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